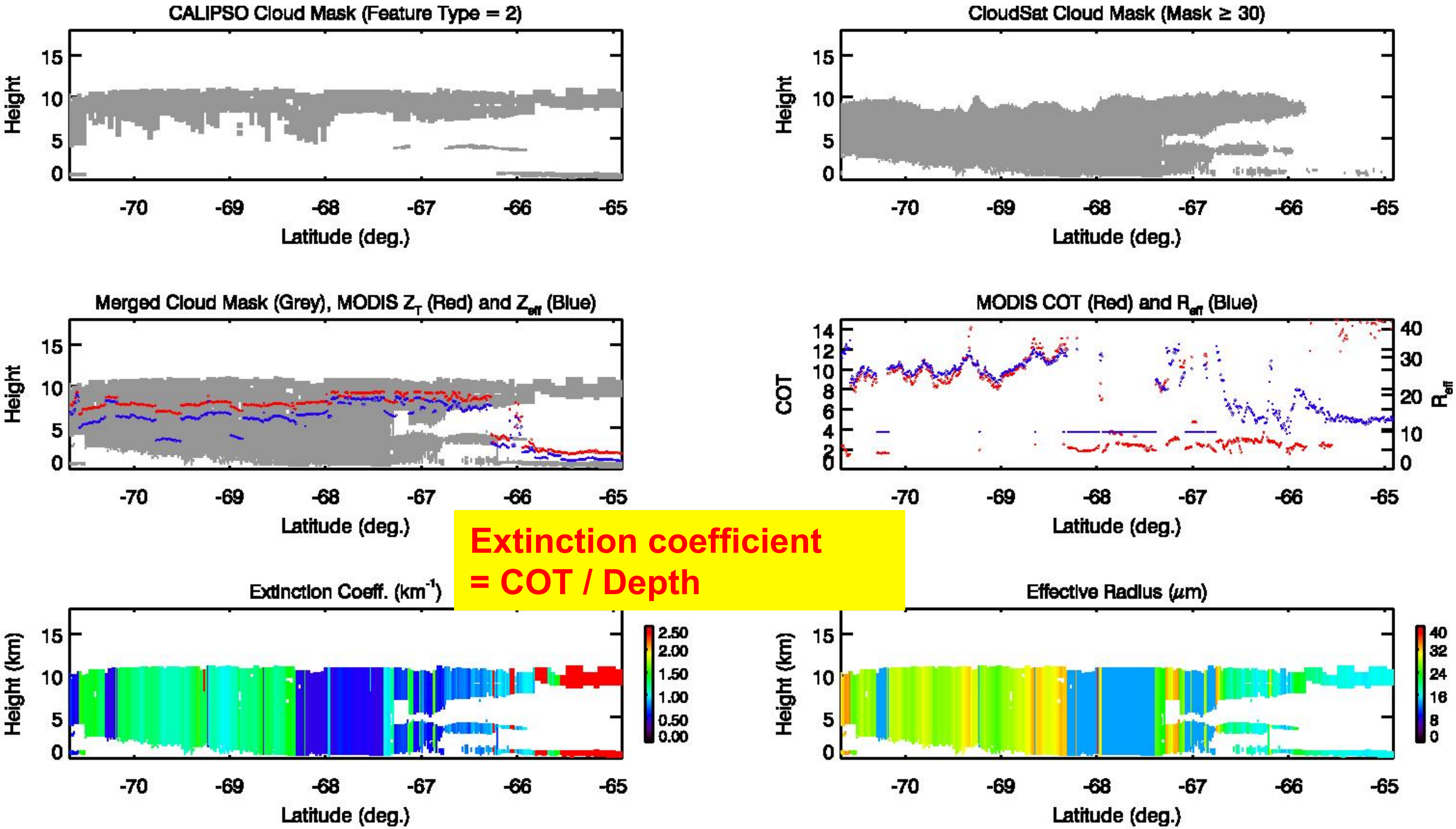
Objectives

- Use CALIPSO/CloudSat/MODIS measurements to construct 3-D cloud field
- Perform 1-D and 3-D simulations for the obtained cloud structure from A-train satellite measurements
- Quantify 3-D radiative effects in estimating earth radiation budget
- Evaluate surface and TOA irradiances computed with a 1-D model for the clouds and the earth's radiation system (CERES) project

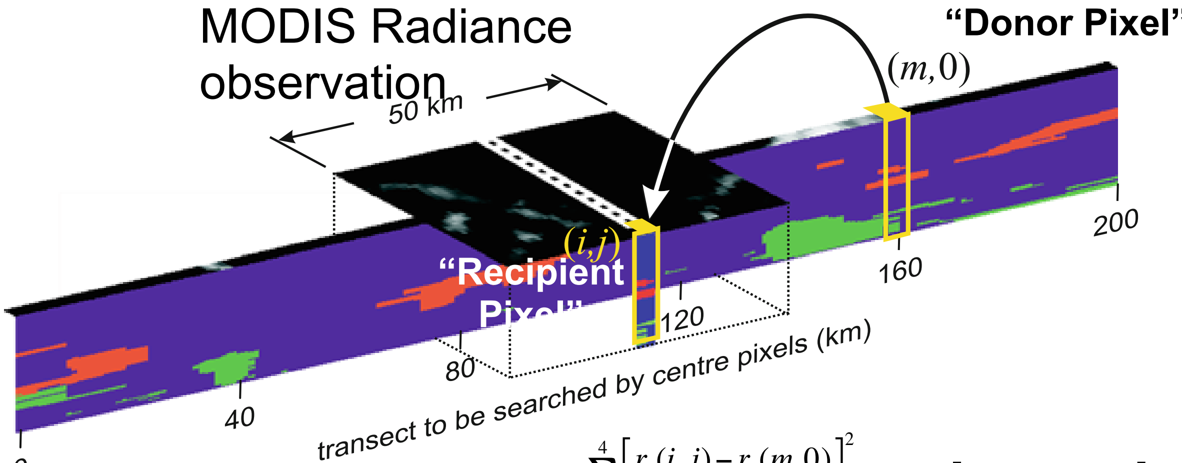
Collocated CloudSat & CALIPSO & MODIS Data Along the A-train Satellite Track (Kato et al., 2010)



Extinction coefficient = COT / Depth

- Merged cloud boundaries from CloudSat and CALIPSO heights (Kato et al., 2010)
- Homogeneous assumption between cloud top and base heights

3-D Cloud Construction Algorithm
(Barker et al., 2011, QJRMS)

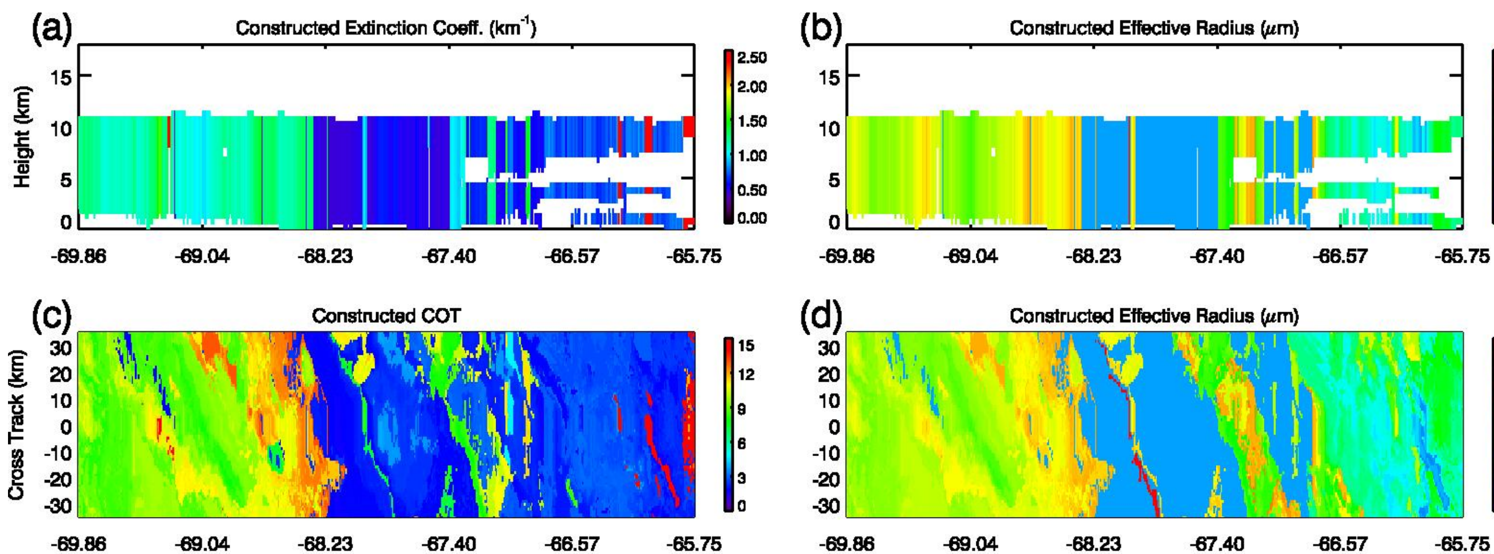


$$F(i,j;m)=\sum_{i=1}^{4}\left[\frac{r_k(i,j)-r_k(m,0)}{r_k(i,j)}\right]^2,\quad m\in\left[i-100,i+100\right]$$

Cloud properties between two close pixels are similar if the two pixels have similar TOA radiances at multiple channels, given that atmospheric and surface conditions do not vary too much (Barker et al., 2011).

Cross-Sectional Images

Down-looking Images



Optical Properties

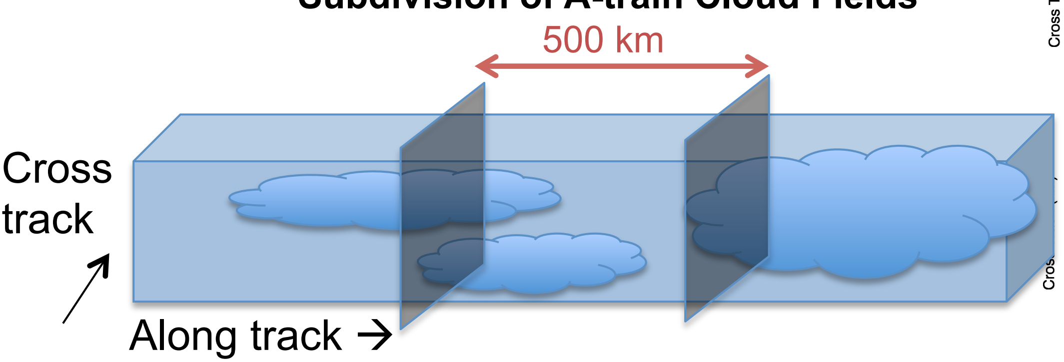
Surface	**Ocean surface albedo**	LUT based on observation data ~ a function of SZA (Jin et al., 2004)
Gas Molecule	**Mid-latitude summer**	◆ p, z, T, H_2O, O_3 profiles at 63 levels ◆ Rayleigh scattering using p and T profiles ◆ Gas absorption is estimated using correlated-K method for subdivided 18 solar bands
Cloud	**MODIS optical properties & CloudSat/CALIPSO cloud boundary**	◆ MODIS cloud optical thickness (COT) ◆ MODIS effective radius ◆ MODIS cloud phase (fixed for one column) ◆ Merged cloud top and base boundaries from CloudSat and CALIPSO ◆ MODIS effective cloud height only if both CloudSat and CALIPSO are not available ◆ Mie scattering data for water clouds for 18 bands Yang scattering data (Yang et al., 2003, 2005) for ice clouds for 18 bands
Aerosol	**Ignored**	

Monte Carlo Model

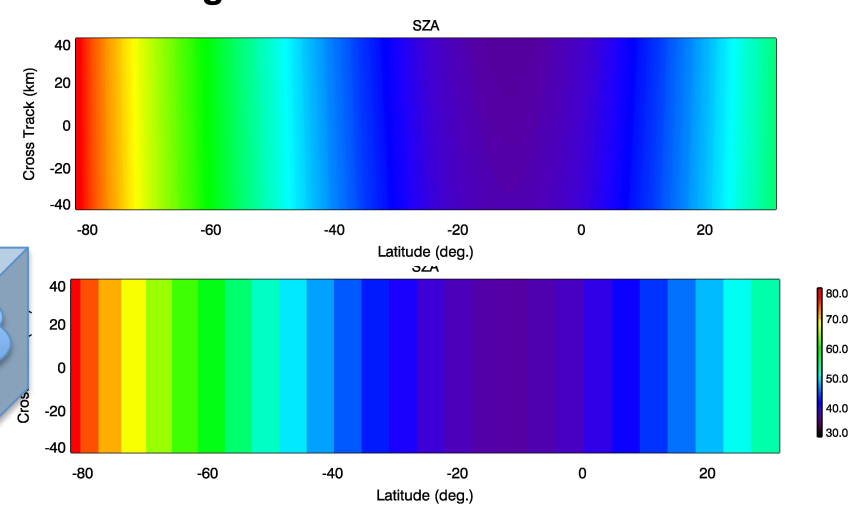
Intercomparison of 3D Radiation Code (I3RC) Community Monte Carlo Model (Cahalan et al., 2005; Pincus, 2009)

- Subdivide domain every 500 km with a 100-km margin at both sides and use constant solar angle for the each sub-domain
- # of photons = 10^4 x # of columns in domain/ cyclic condition at side boundary
- To obtain shortwave (SW) broadband (BB) fluxes from 0.2 μm to 4.0 μm, narrowband calculation is performed for subdivided 18 bands, and the results are combined.
- Two options for the simulation
  1) 1D Independent column approximation (ICA): photons move vertically only.
  2) 3D simulation: Photons moves three-dimensional direction.

Subdivision of A-train Cloud Fields



Averaged SZA for each sub-domain

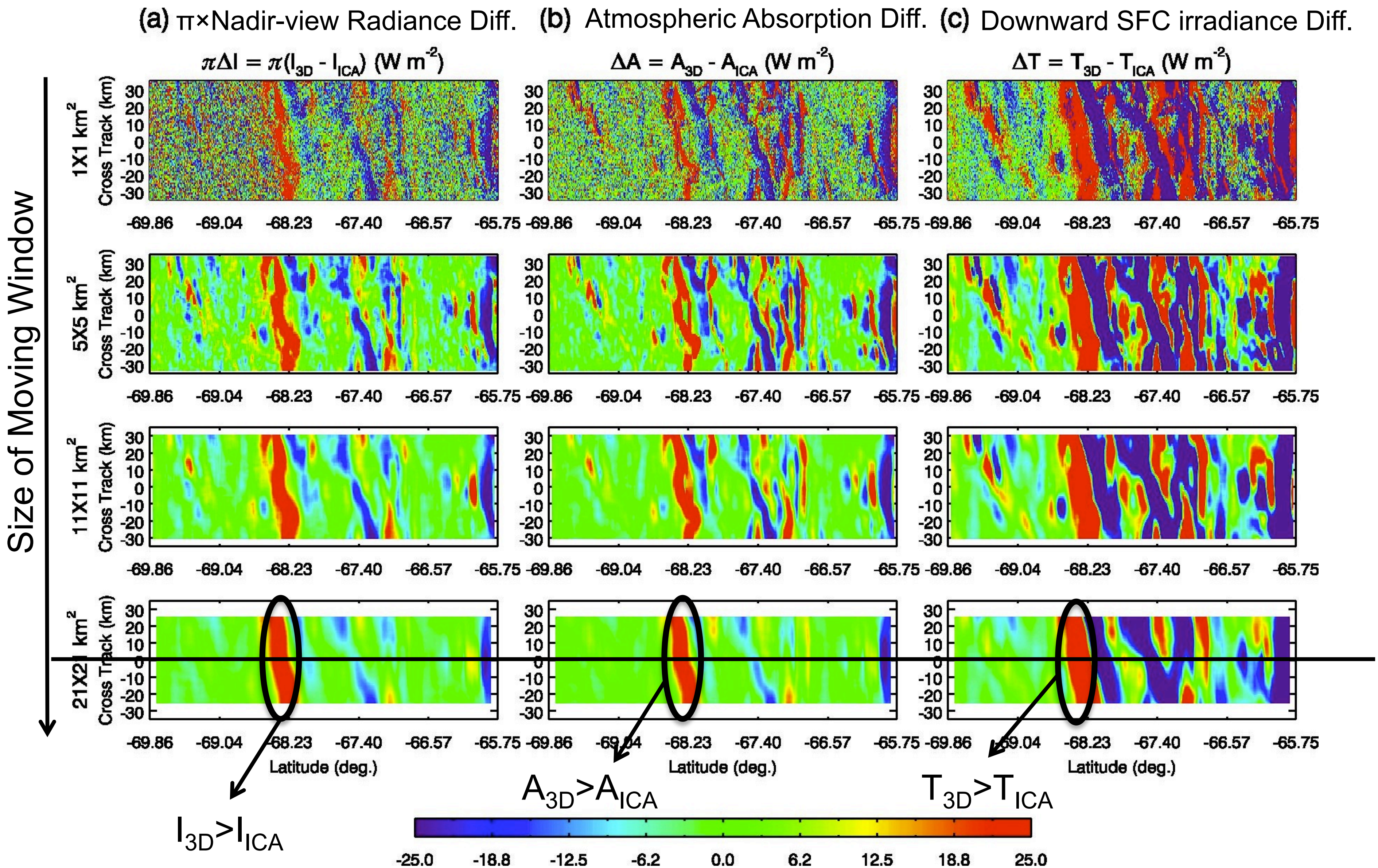


Definition of Difference between 3-D and 1-D

"**Difference**" = **3-D** minus **1-D** **(in unit of W m^{-2})**

$\pi\Delta I = \pi(I_{3D} - I_{ICA})$	π × TOA Nadir-view Radiance
$\Delta A = A_{3D} - A_{ICA}$	Atmospheric Absorption
$\Delta T = T_{3D} - T_{ICA}$	Downward SFC irradiance

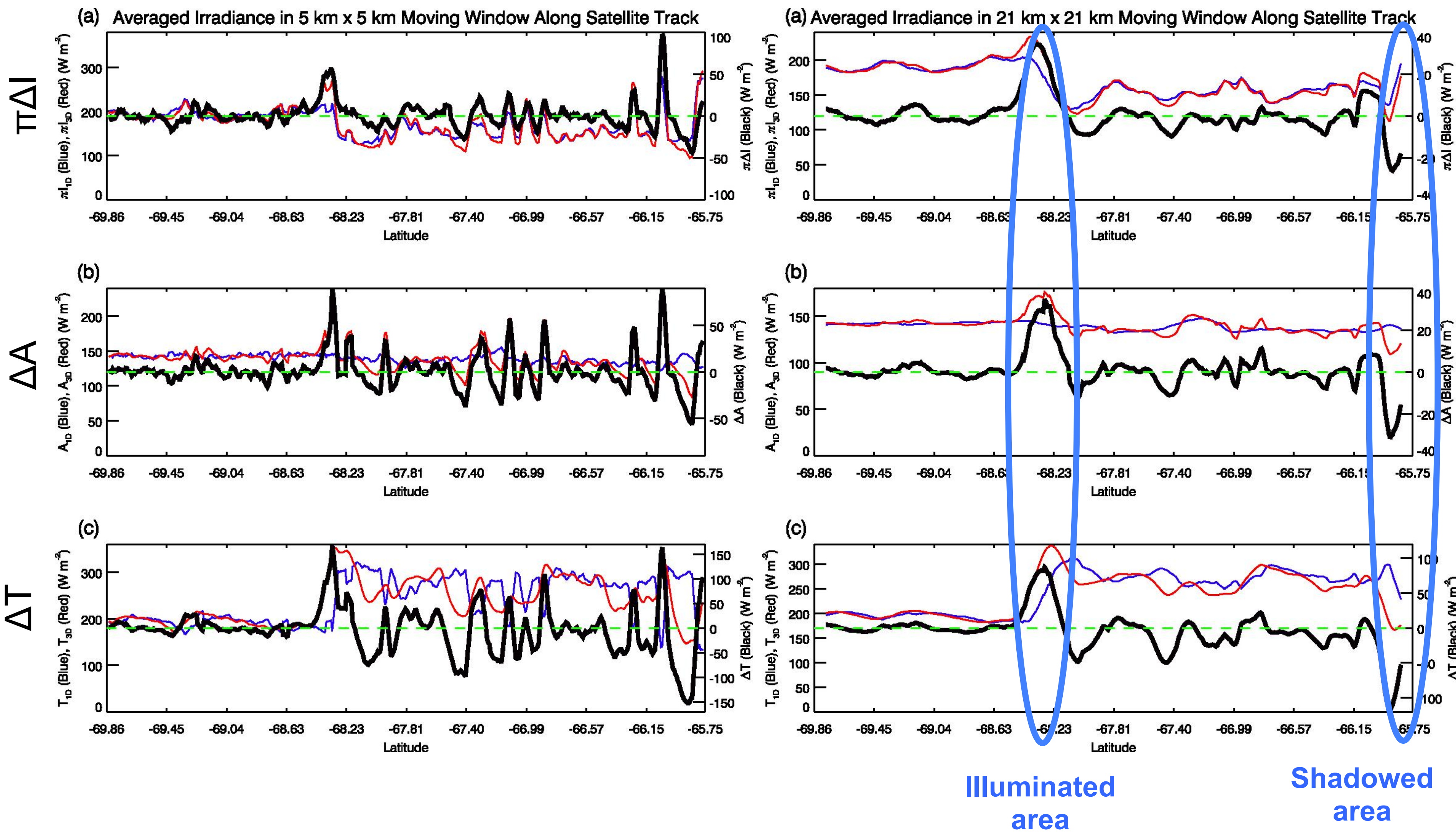
Spatial Distribution of $\pi\Delta I$, ΔA, and ΔT



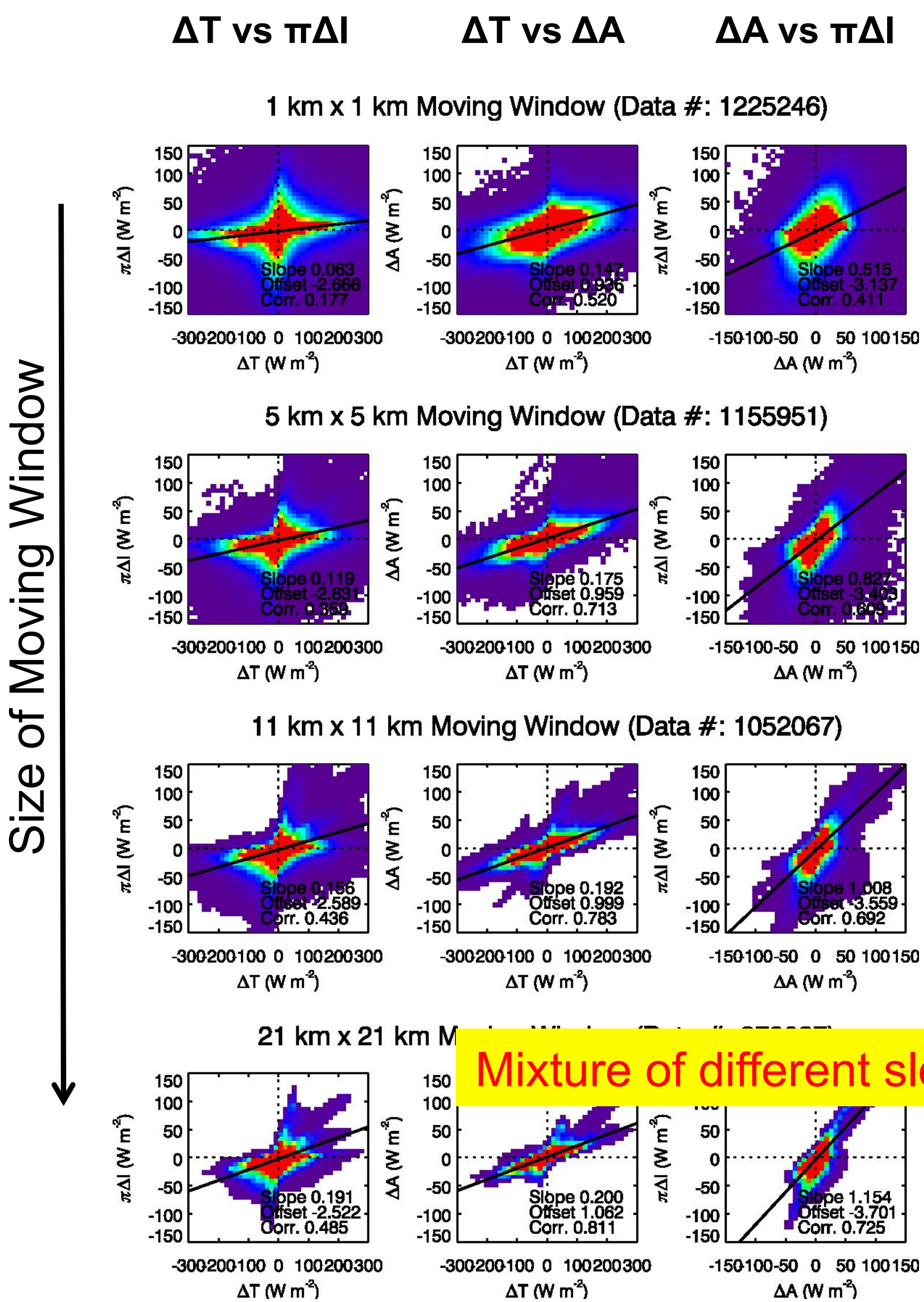
Distribution of πΔI, ΔA, and ΔT

5 km x 5 km Moving Window

21 km x 21 km Moving Window



Positive Linear Relations Among πΔI, ΔA, and ΔT



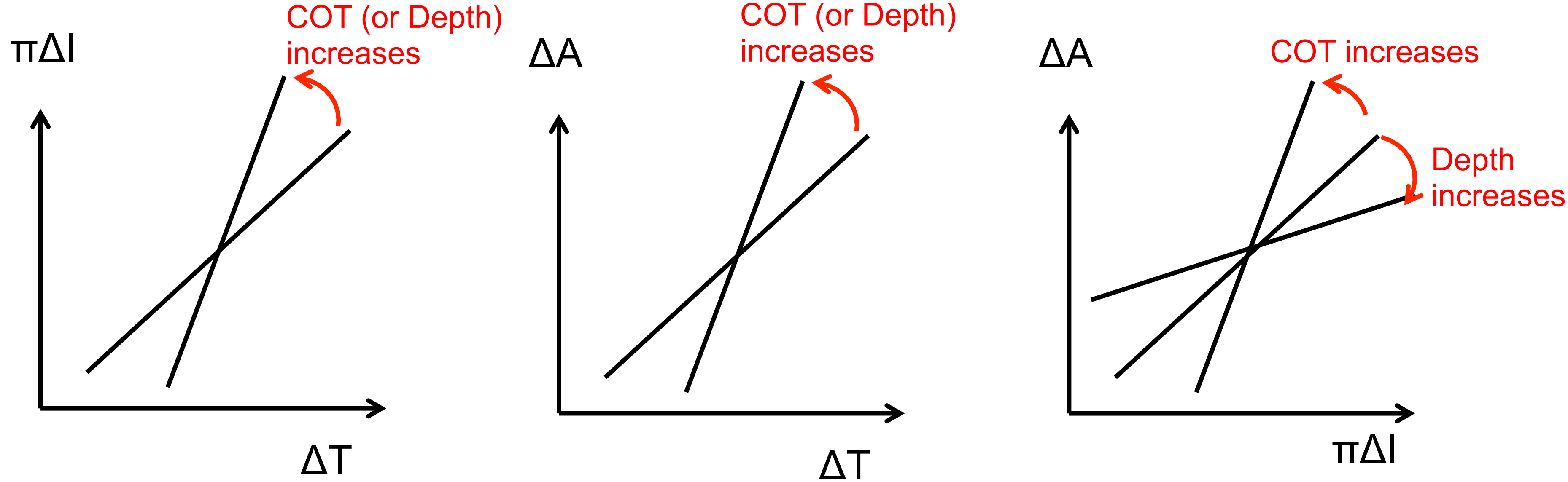
Linear relationships among πΔI, ΔA, and ΔT emerge, as scale increases (> 5 km).

➔ In the illuminated (shadowed) area, 3D effects increase (decrease) I, A, and T. Those changes are linearly correlated.

➔ In the smaller scale (~ 1 km), linear relationship is not apparent due to (1) Monte Carlo noise and (2) slight location differences of peaks in πΔI, ΔA, and ΔT .

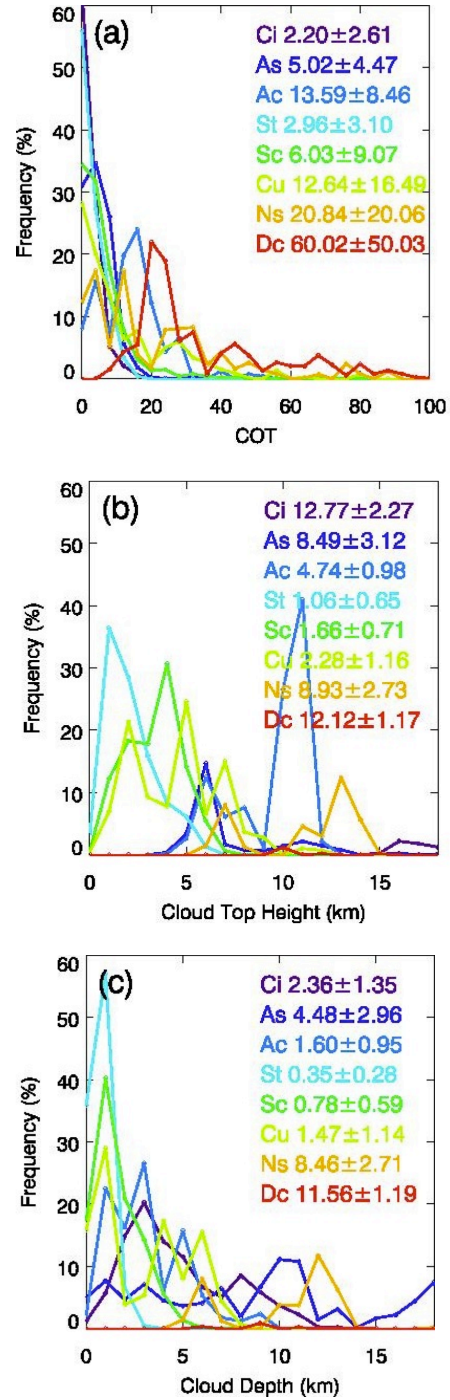
Factors Influencing on the Relations among πΔI, ΔA, and ΔT

	COT increases	Cloud depth increases	SZA increases
πI (or πΔI)	increase	increase	decrease
A (or ΔA)	increase	increase	increase
T (or ΔT)	decrease	decrease	increase
πΔI/ΔT	increase	increase	decrease
ΔA/ΔT	increase	increase	-
πΔI/ΔA	increase	decrease	decrease

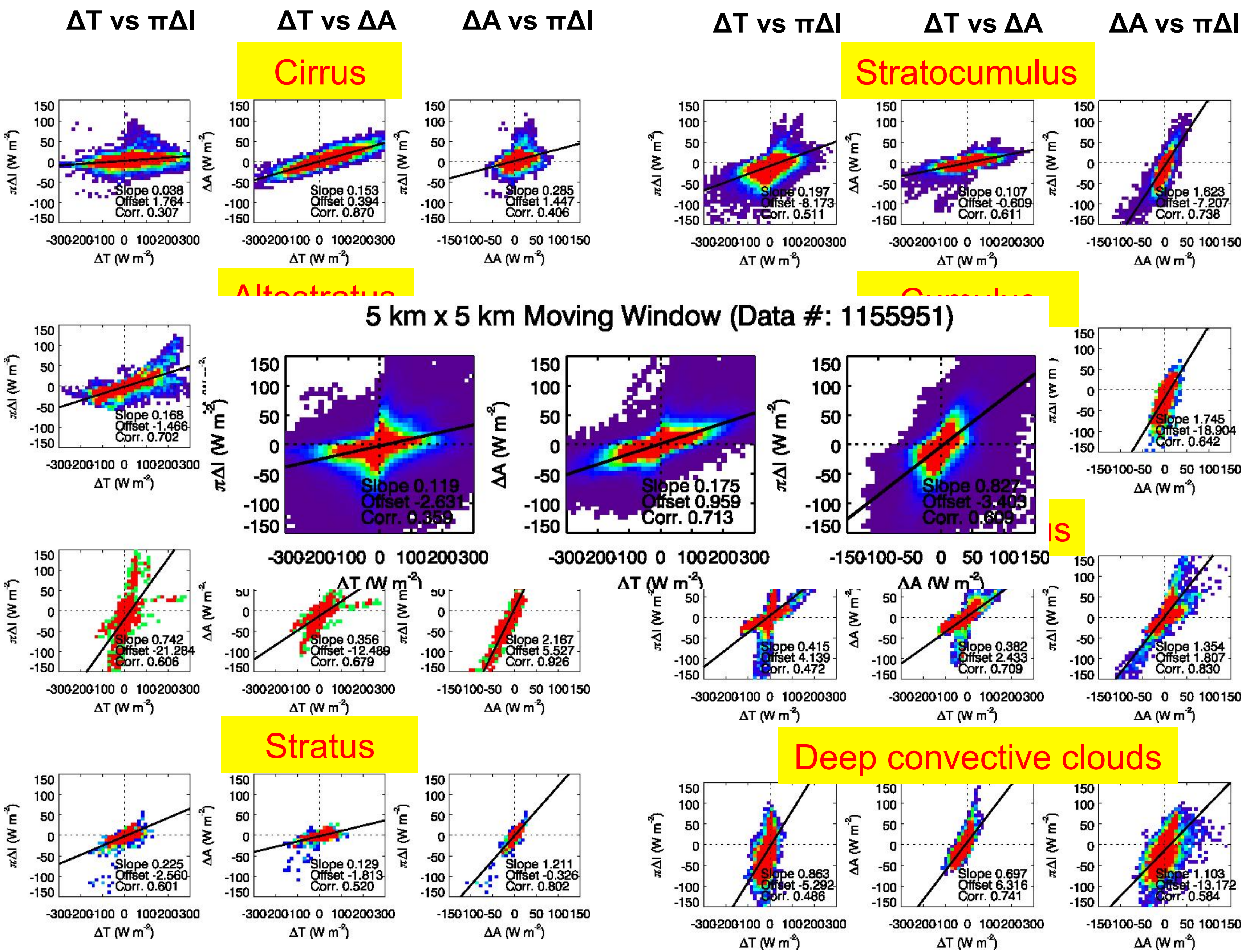


Cloud Properties of Eight Cloud Types

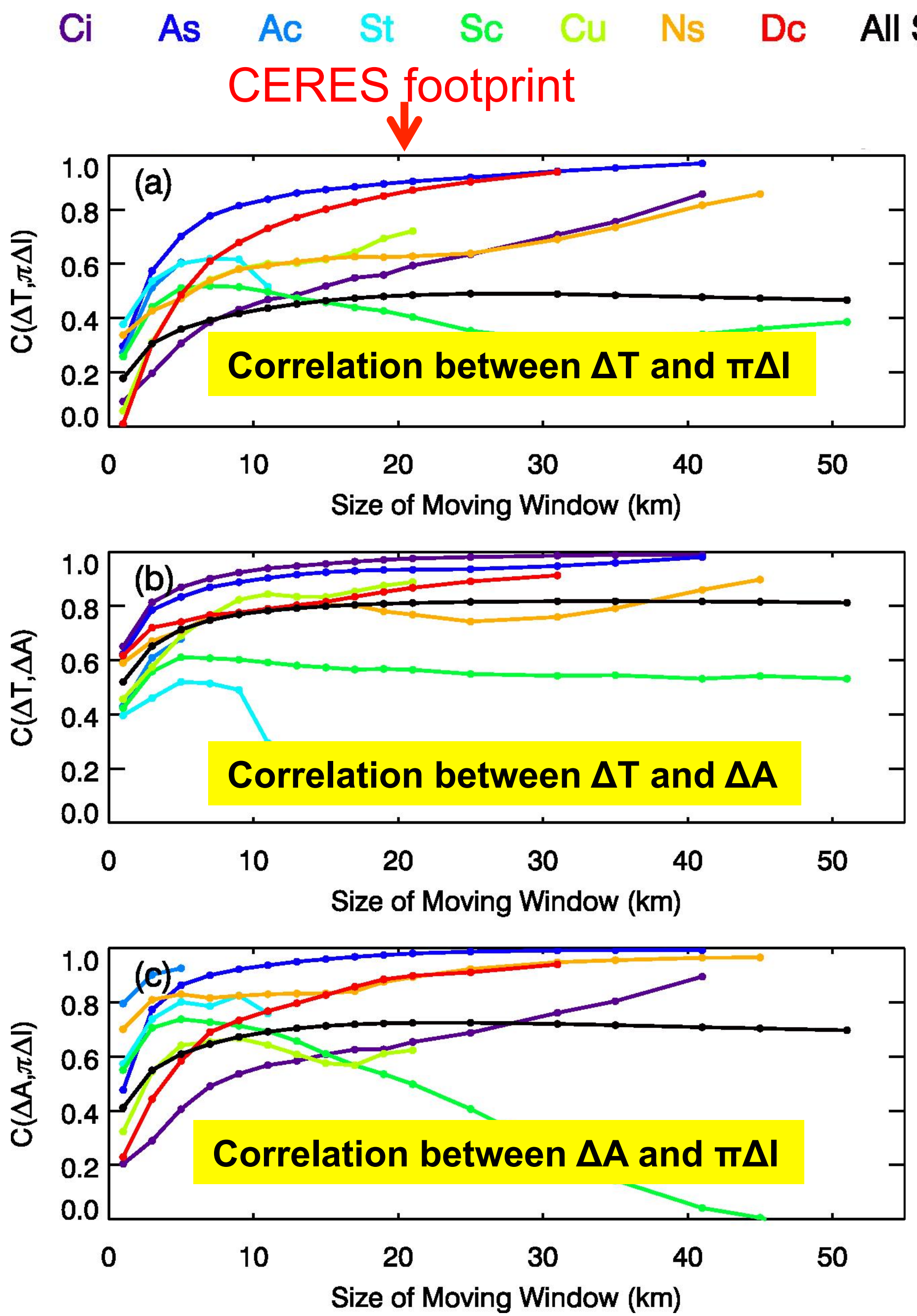
Cloud Type	Horizontal Dimension	Vertical Dimension	Base Height	Precipitation
Cirrus (Ci)	10^3 km	Moderate	> 7 km	None
Altostratus (As)	10^3 km Homogeneous	Moderate	2-7 km	None
Altocumulus (Ac)	10^3 km Inhomogeneous	Shallow or moderate	2-7 km	Virga possible
Stratus (St)	10^2 km Homogenous	Shallow	0-2 km	None or slight
Stratocumulus (Sc)	10^3 km Inhomogeneous	Shallow	0-2 km	Drizzle or Snow possible
Cumulus (Cu)	1 km Isolated	Shallow or moderate	0-3 km	Drizzle or Snow possible
Nimbostratus (Ns)	10^3 km	Thick	0-4 km	Prolonged rain or snow
Deep convective clouds (Dc)	10 km	Thick	0-3 km	Intense shower of rain or hail possible



Cloud Type-Dependent Relations among πΔI, ΔA, and ΔT



Cloud Type-Dependent Relations among πΔI, ΔA, and ΔT



ΔI, ΔA and ΔT are linearly correlated well, especially cloud scenes are separated by cloud type.

$\Delta I \Rightarrow \Delta A$ or ΔT

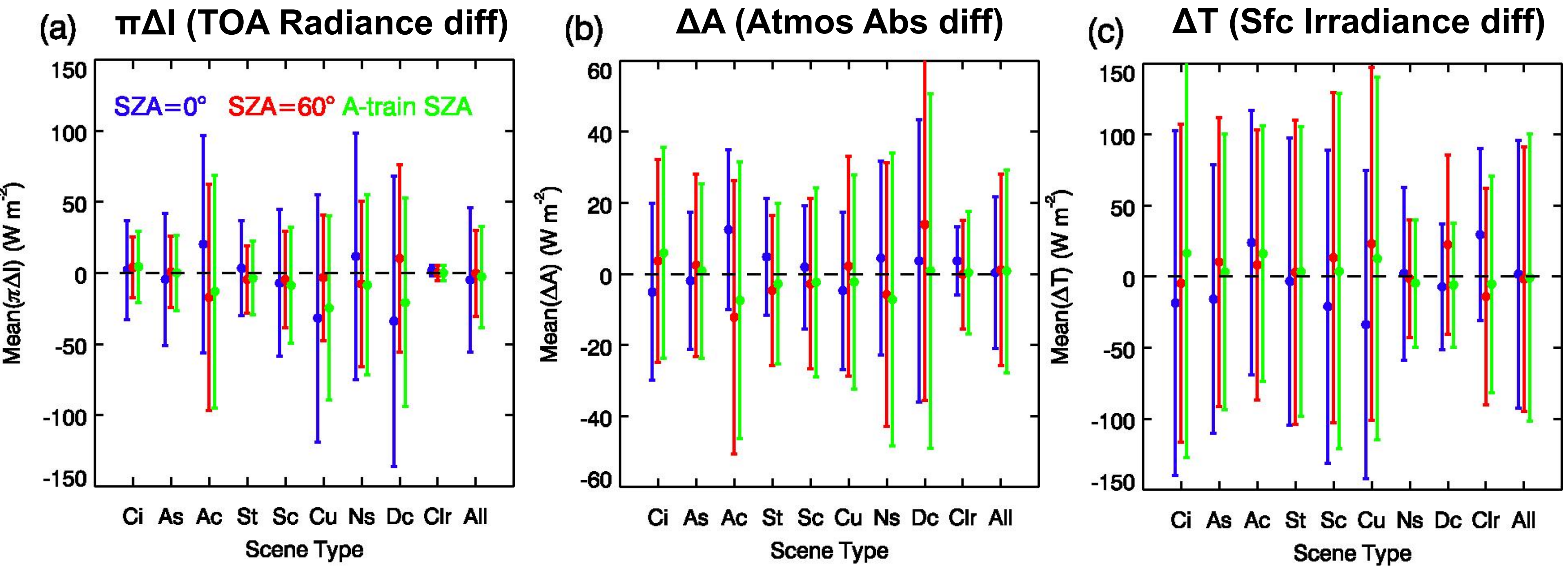
$A_{3D} - A_{ICA}$

$T_{3D} - T_{ICA}$

$\Delta I = I_{3D} - I_{ICA}$

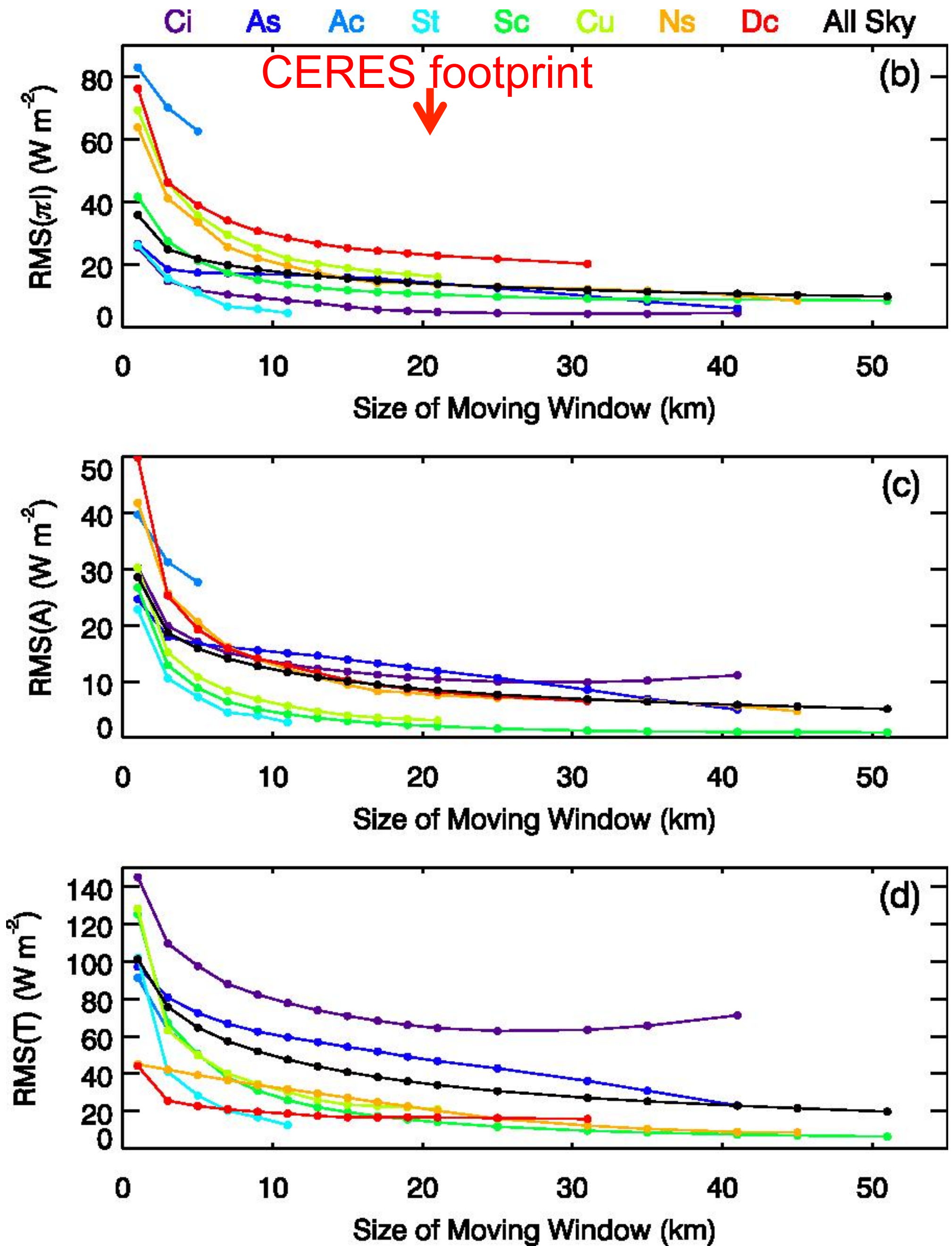
= {CERES-measured TOA radiance} minus {1D-modeled nadir view radiance}

Domain-Averages of 3D Minus 1D Irradiances



- Domain-averages of πΔI, ΔA, and ΔT are nearly zero (< 3 W m^{-2}).
- Averages of πΔI, ΔA, and ΔT become larger when cloud scenes are separated by cloud type, up to 25, 8,and 17 W m^{-2}, respectively.
- ΔA shows the smaller standard deviation than those of πΔI or ΔT.

RMS Difference between 3D and 1D Irradiances



- RMS difference is much larger than mean difference between 3D and 1D results.
- RMS difference dramatically drops between 1 km and 10 km scales, which is consistent with those obtained from the earlier studies (O'hirok and Gautier, 2005; Wyser et al., 2005).

Summary

- Collocated MODIS, CloudSat, and CALIPSO datasets (Kato et al., 2010) are used to construct three-dimensional (3D) cloud structure (Barker et al. 2011).
- CloudSat cloud type is expanded in merged cloud layer by searching the closest CloudSat pixel.
- One-dimensional independent column approximation (ICA) and full 3D simulations are achieved using the same Monte Carlo model.
- The 3D minus 1D irradiances in TOA, atmosphere, and surface are linearly correlated each other (referred as $\pi\Delta I$, ΔA, and ΔT, respectively).
- Each cloud type has its own relation among $\pi\Delta I$, ΔA, and ΔT. The correlation among $\pi\Delta I$, ΔA, and ΔT increases with the scale, and reaches to maximum at 20 km. If the $\pi\Delta I$ is estimated from the satellite measurements, ΔA, and ΔT can be inferred from the linear relations.
- RMS differences between 3D and ICA irradiances largely decrease at scales between 1 km and 10 km.

Relations among πΔI, ΔA, and ΔT (Barker et al., 2012)

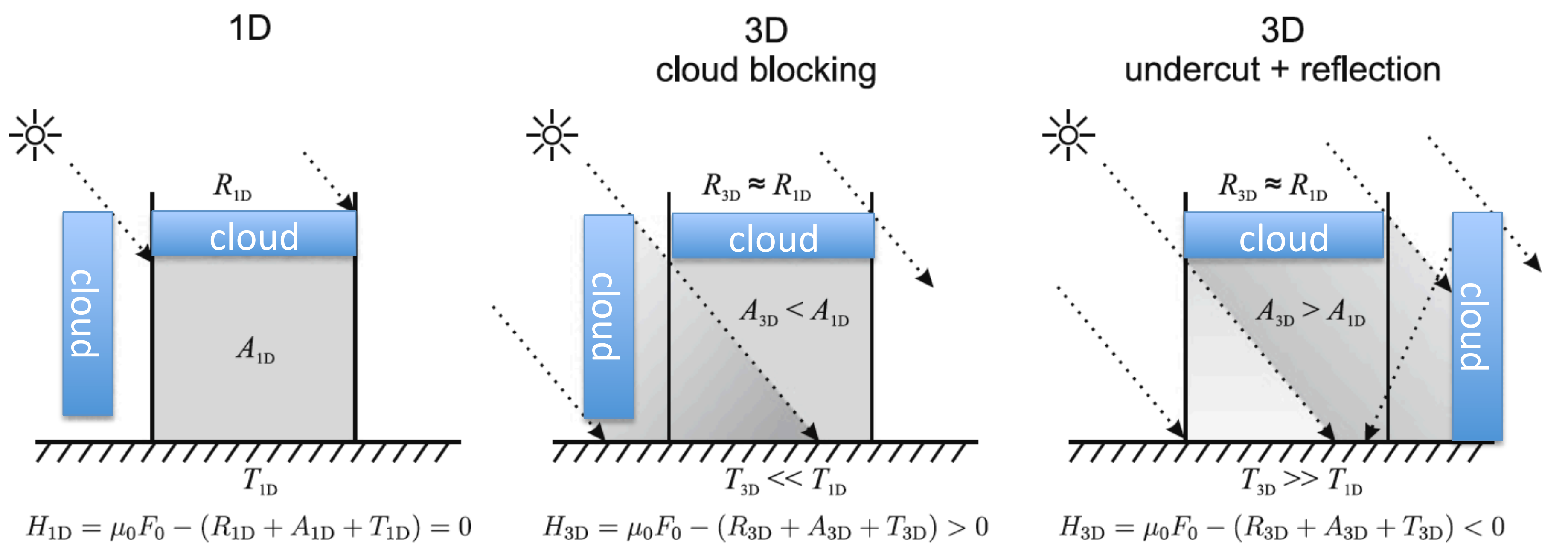
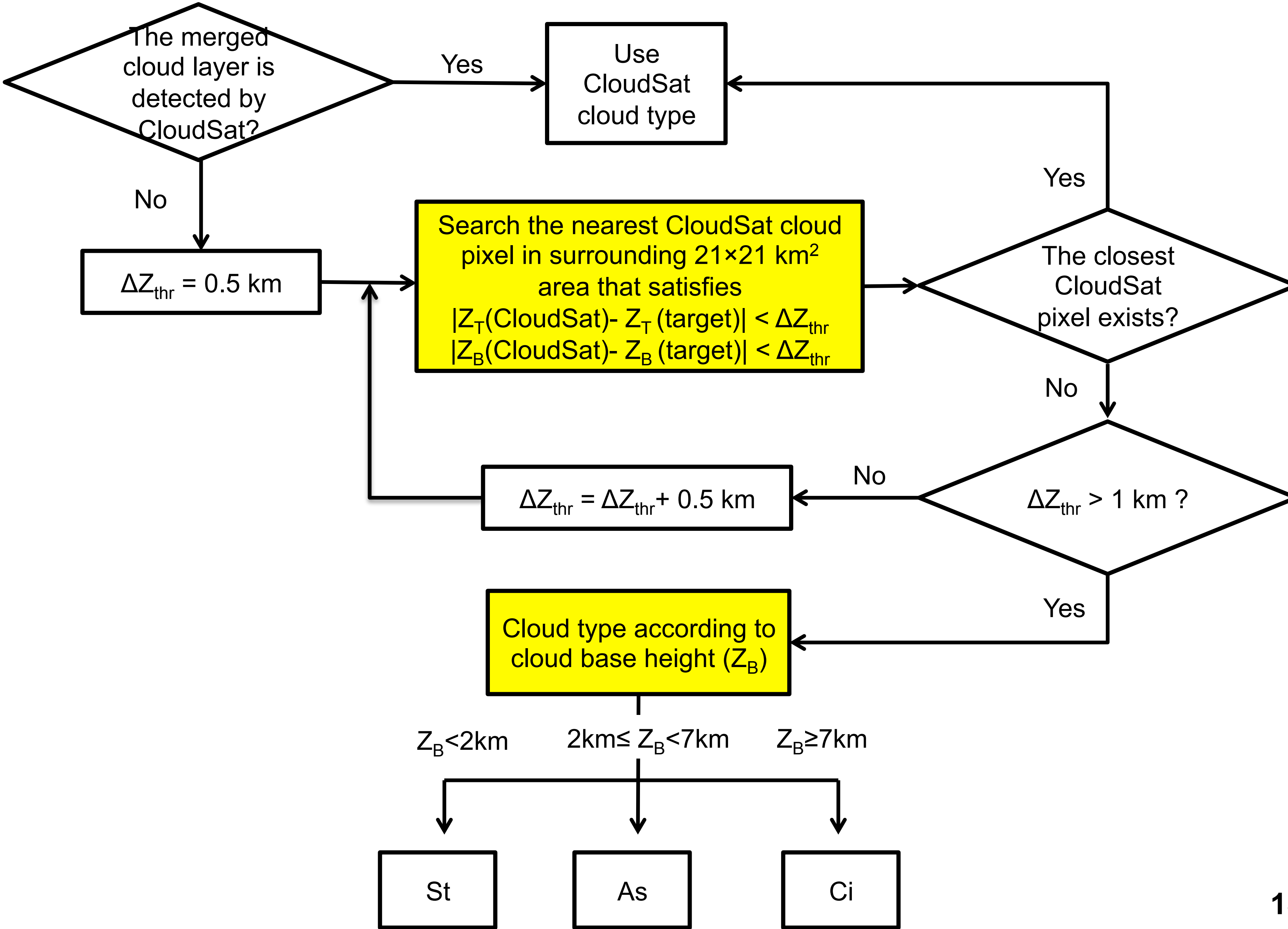
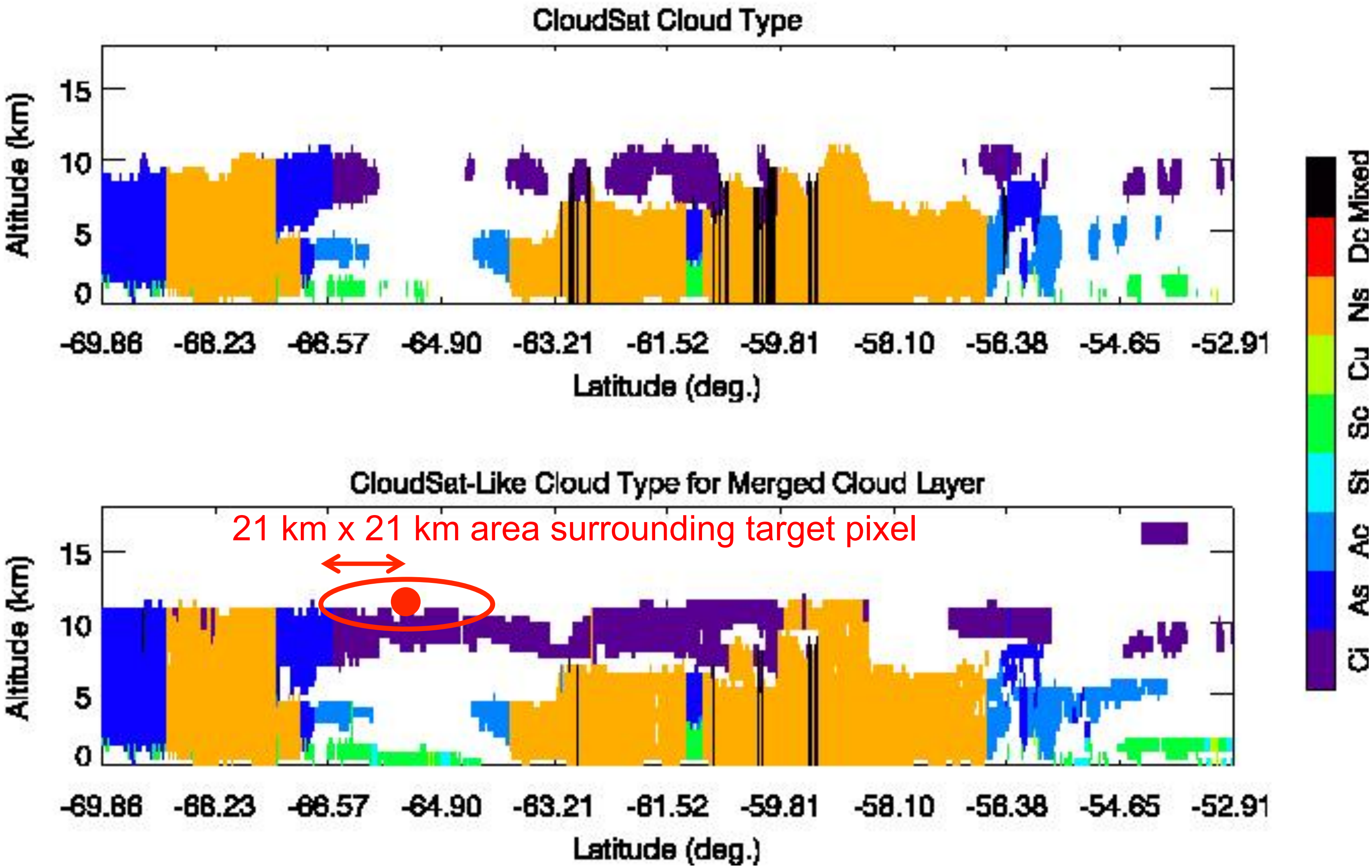


Fig. 11 Schematic diagram illustrating horizontal transport H of solar radiation. The *column* of concern is in the *centre* of each figure and consists of an overcast cloud. R, A and T denote reflectance, atmospheric and surface absorptance, respectively. *Left figure* shows 1D results where there is no transfer through the column's vertical sides and so $H_{1D} = 0$. The other figures show the impact on H_{3D} due to clouds outside the column of concern

Cloud Type for the Merged Cloud Layers



Cloud Type for the Merged Cloud Layers



Eight Cloud Types Defined in CloudSat Algorithm

Cloud Type	Horizontal Dimension	Vertical Dimension	Base Height	Precipitation
Cirrus (Ci)	10^3 km	Moderate	> 7 km	None
Altostratus (As)	10^3 km Homogeneous	Moderate	2-7 km	None
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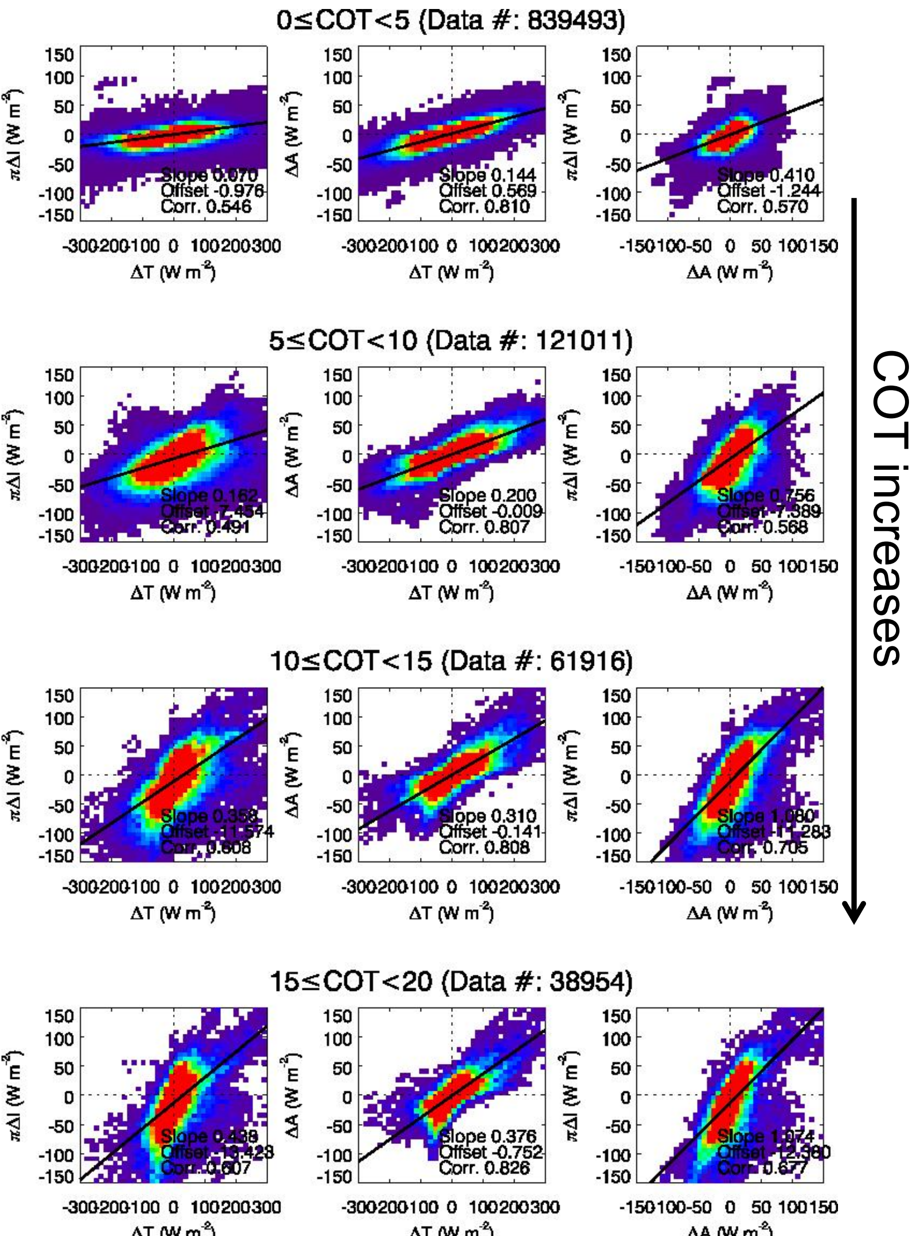
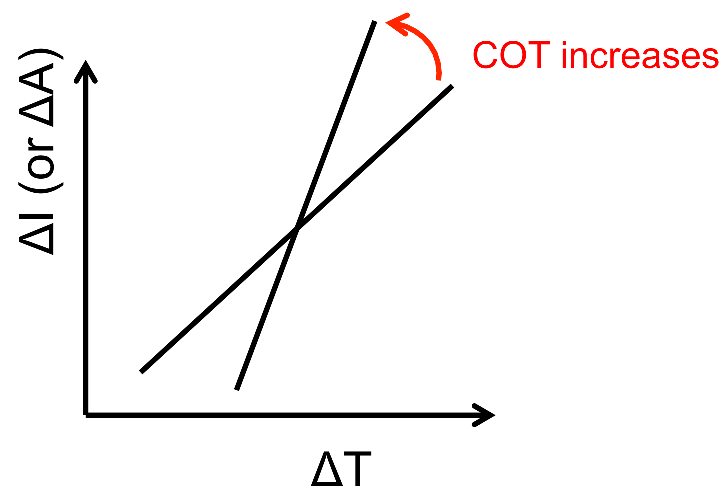
Effects of COT on the Relations among πΔI, ΔA, and ΔT

Different COT

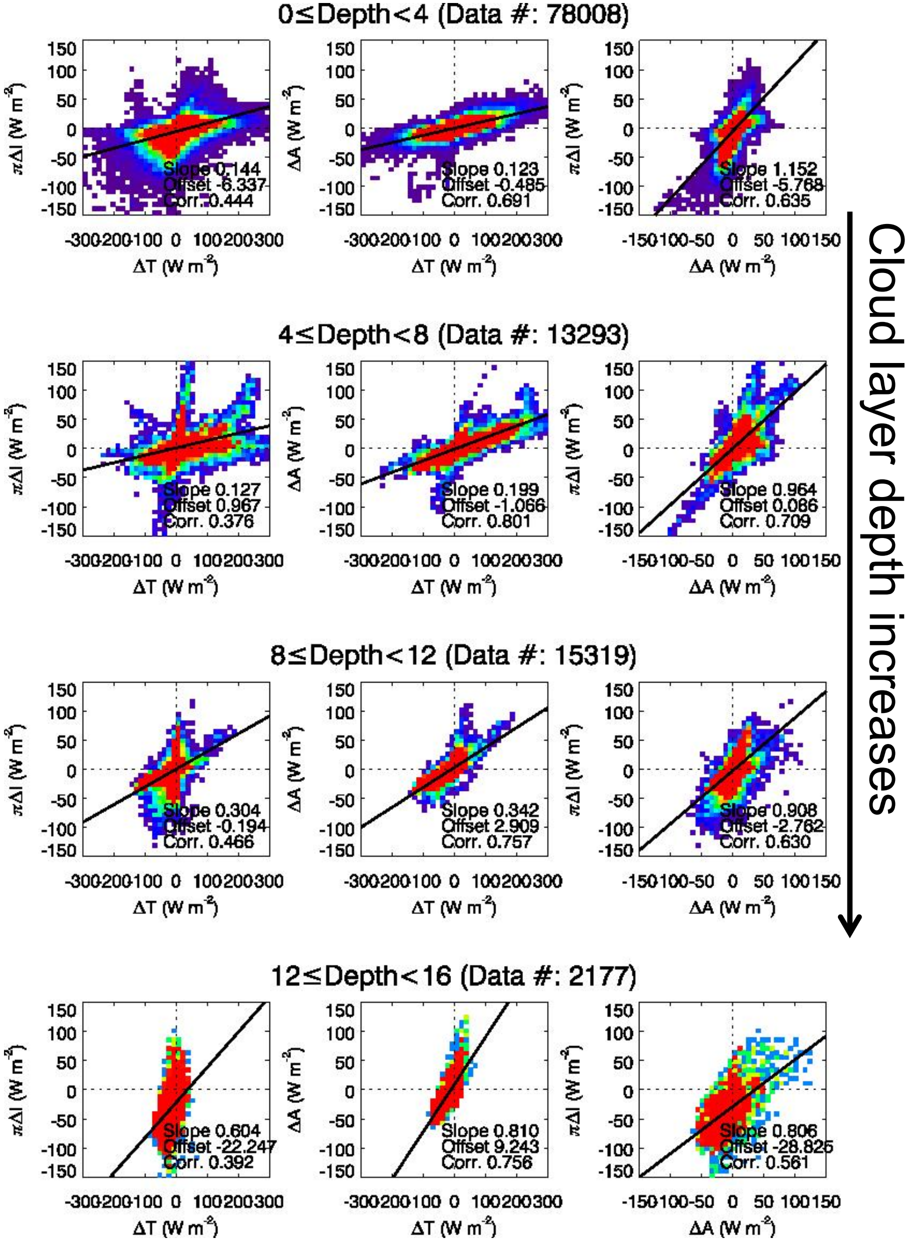


	For larger COT
πI (or πΔI)	increase
A (or ΔA)	increase
T (or ΔT)	decrease
πΔI/ΔT	increase
ΔA/ΔT	increase
πΔI/ΔA	increase



Effects of Depth on the Relations among πΔI, ΔA, and ΔT

Different Cloud Depth (km)



	For larger cloud depth	For larger SZA
πI (or πΔI)	increase	decrease
A (or ΔA)	increase	increase
T (or ΔT)	decrease	increase
πΔI/ΔT	increase	decrease
ΔA/ΔT	increase	-
πΔI/ΔA	decrease	decrease